TR 1729—Fiber Optic Seals: Glass and Plastic Fiber Optic Safing Systems for International Safeguards and Arms Control Applications —by R R Ulrich

Fiber Optic Seals: Glass and Plastic Fiber Optic Safing Systems for International Safeguards and Arms Control Applications

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The Harry Diamond Laboratories has developed a tamper-resistant/tamper-indicating safing system for the U. S. Arms Control and Disarmament Agency. The safing system consists of a fiber optic seal and related equipment that assembles, photographs, and identifies the seals in the field. Such seals are needed for the effective use of containment as a safeguards technique and for the

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protection of unattended instruments used for surveillance at peaceful nuclear facilities.

Described are both glass and plastic fiber optic seals that are reliable and simple to assemble in the field. Existing fiber optic seal inspection equipments are evaluated, and a system is proposed for operational use.

CONTENTS

FIGURES

FIGURES (CONT'D)

1. INTRODUCTION

Since the latter part of 1970, the Harry Diamond Laboratories (HDL) has been engaged in the development of a secure (tamper-resistant/tamper-indicating) safing system for the U.S. Arms Control and Disarmament Agency (ACDA). Such a system is of concern to ACDA because it is needed to effectively implement and verify certain international arms control or safeguards agreements. Under provisions of the Treaty on the Nonproliferation of Nuclear Weapons, the International Atomic Energy Agency (IAEA) is responsible for conducting safeguards at peaceful nuclear facilities. Present and projected safeguards activities show the need for a tamper-resistant/tamper-indicating seal that is (1) capable of being uniquely and nondestructively identified in the field, (2) easily adaptable to a variety of situations, (3) simple to install, and (4) relatively inexpensive to produce. Such sealing systems are needed for effective use of containment as a safeguards technique and for the protection of unattended instruments used for surveillance.

A scheme for producing a tamper-resistant seal from the randomly oriented fiber ends of a fiber optic bundle was reported by Lorin R. Stieff of ACDA and Robert G. Hogan of the Corning Glass Works in 1970.[1]

In 1971, HDL delivered to ACDA a prototype model of a portable safing system[2] that uses fiber optic seals and assembles, photographs, and identifies them in the field. Evaluation of this system by ACDA; the Atomic Energy Commission at Brookhaven, and IAEA indicated the need for a seal that was easier to assemble and inspection equipment that was more compact.

In 1973, both an improved fiber optic seal and a compact fiber optic seal inspection system were developed.[3] The present report describes further design improvements in the glass fiber optic seals in section 2. Plastic fibers as a substitute for the glass fibers are considered in detail in section 3. The advantages of the resulting plastic fiber

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[1] *Lorin R. Stieff and Robert G. Hogan, A Progress Report on the Development of a Tamper Resistant Safing System for International Safeguards and Arms Control Applications, IAEA Symposium on Progress in Safeguards Techniques, IAEA/SM-133/113 (July 1970).*

[2] *R. R. Ulrich, Fiber Optic Seals: A Portable System for Field Use in International Safeguards and Arms Control Applications, Harry Diamond Laboratories TR-1571 (October 1971).*

[3] *R. R. Ulrich, Fiber Optic Seals: Improved Seal Assemblies and Inspection Equipment for Field Use in International Safeguards and Arms Control Applications, Harry Diamond Laboratories TR-1669 (July 1974).*

optic seals developed at HDL are pointed out. Existing fiber optic seal inspection systems are evaluated in section 4, and a new system is proposed that appears suitable for operational use.

2. GLASS FIBER OPTIC SEALS

The glass fiber optic seals developed by HDL for ACDA use a fiber optic bundle consisting of 225 glass fibers within a clear polyvinyl sheathing. The fibers have a nominal diameter of 0.0025 in. The two ends of the fiber bundle are looped together and secured in a common collar. When light is directed onto the fiber ends in one half of the collar opening, the fiber ends in the opposite half of the collar opening form a unique fingerprint.

The initial field-assembled glass fiber optic seal[2] developed at HDL is shown in figure 1(a). The fibers were secured in the collar by epoxy, requiring a tedious assembly procedure in the field. An improved fiber optic seal[3] was developed that was much easier to assemble. This

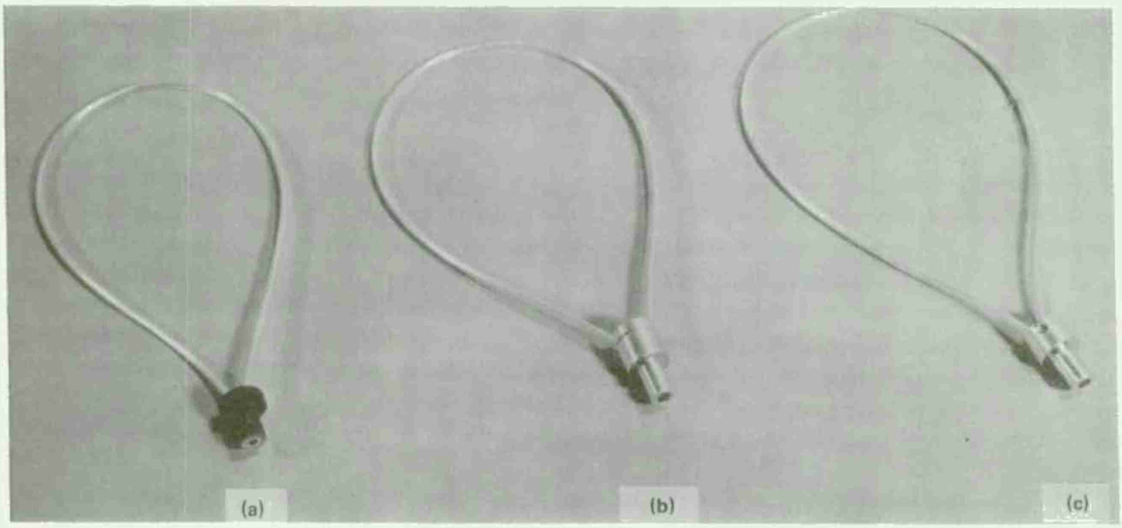

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Figure 1. Glass fiber optic seals with (a) epoxy filler, (b) lead filler and bundle support disk, and (c) lead filler and set screw bundle support.

[2] *R. R. Ulrich, Fiber Optic Seals: A Portable System for Field Use in International Safeguards and Arms Control Applications, Harry Diamond Laboratories TR-1571 (October 1971).*

[3] *R. R. Ulrich, Fiber Optic Seals: Improved Seal Assemblies and Inspection Equipment for Field Use in International Safeguards and Arms Control Applications, Harry Diamond Laboratories TR-1669 (July 1974).*

seal, shown in figure 1(b), uses a lead filler pressed into the front of the collar to hold the fibers in position and a disk at the rear of the collar to mechanically secure the fiber bundle. Further improvements have been made to this seal assembly by replacing the disk with two set screws through the side of the collar pressing against the polyvinyl sheathings of the fiber optic bundle (fig. 1(c)). The screws remain in the collar, and the fiber optic bundle is secured at each end by tightening the screws. The lead filler that is pressed into the front of the collar is still used.

3. PLASTIC FIBER OPTIC SEALS

3.1 Plastic Fibers--General Characteristics and Availability

Plastic fibers were considered in place of glass fibers to produce a fiber optic seal that would be easier to assemble in the field. Information was compiled for HDL by Controlled Environment Systems, Inc., of Rockville, MD, on the availability and suitability of plastic fibers for seal fabrication. This information was used in this study.

Plastic fibers transmit light by total internal reflection through a core material having an index of refraction somewhat greater than the cladding material. A typical plastic fiber consists of a core of highly transparent polystyrene of 1.60 index and a thin cladding of transparent methyl methacrylate of 1.49 index. The acceptance angle of a typical fiber is 64 to 70 deg with a numerical aperture of 0.58. Plastic fibers are usable from -40 to +180°F. The light losses in plastic fibers are about 10 percent/ft and a total of 30 percent due to end losses. In contrast to those of glass, the transmission characteristics of plastic fibers are actually improved under gamma radiation; the light transmission of normal glass degrades to zero under radiation.

Single-strand plastic fibers are generally available with diameters as small as 0.005 in., but diameters of 0.003 and even 0.001 in. are available as special items. Plastic fiber optic bundles or light guides of many individual fibers are available with fibers only having diameters of 0.010 in. or greater.

3.2 Seal Development and Description

In developing plastic fiber optic seals, various types of plastic fiber optic bundles or light guides were used. The commercially available light guides consist of a maximum of 64 fibers of 0.010-in. diam. These light guides did not provide enough light centers in the

fingerprints of the seals to insure uniqueness by the random orientation of the fiber ends. However, striations in the plastic fiber ends were clearly evident and added a unique character to the fingerprints.

To produce seals with fibers of smaller than 0.010-in. diam, special fiber bundles were constructed at HDL. They consisted of both 0.003 and 0.005-in.-diam plastic fiber optics. The individual fibers were cut into 30-cm lengths and fed into a polyvinyl sheathing. The fiber bundles are easy to construct, provided that the bundle length is kept under several meters; their estimated production cost does not appear prohibitive for this application.

Two methods of assembly were developed for use with the plastic fiber optic bundles. Both methods utilize the flexibility and nonbrittleness of plastic to hold the fibers securely into the collar.

The first method uses a collar with a conical hole that is threaded at its narrow end as shown in figure 2(a). The plastic fibers are twisted into the collar and are secured firmly in place as the

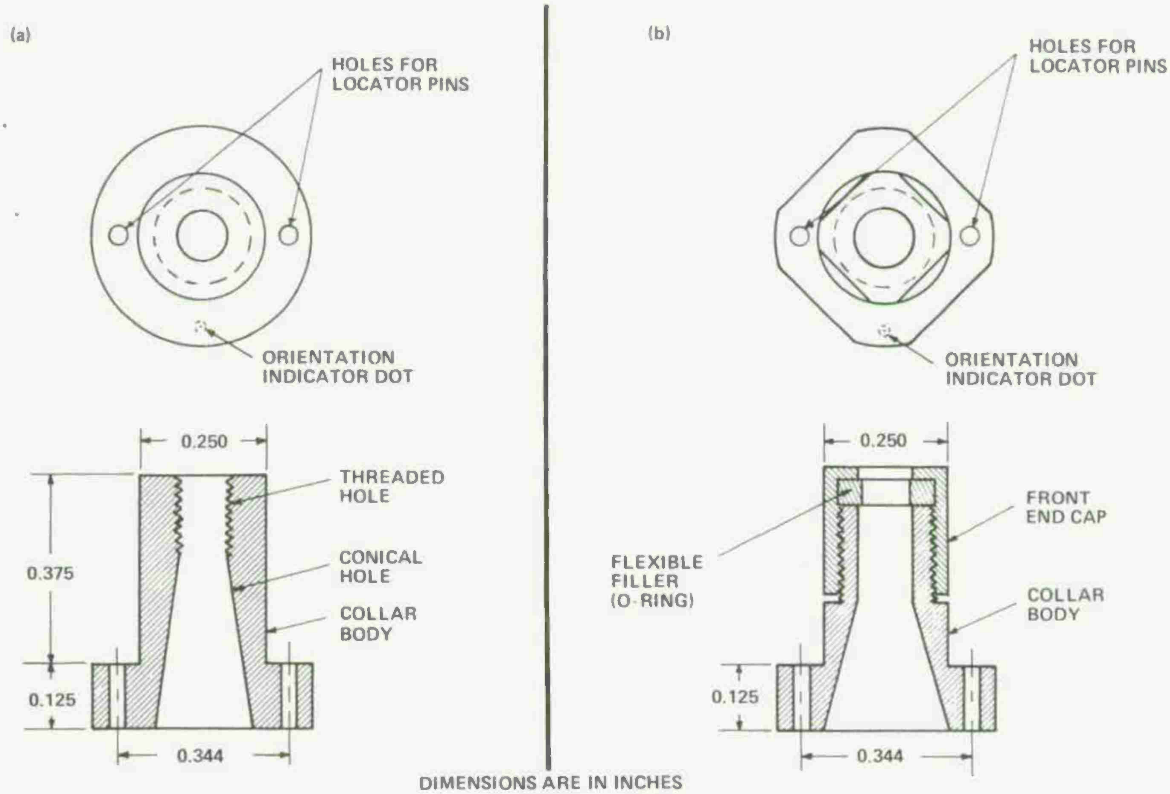

Figure 2. Plastic fiber optic seal collars. (a) Fibers are secured in threaded hole. (b) Fibers are secured by compressed O-ring.

fibers engage in the threads. With a sharp knife, the fibers are cut even with the front end of the collar, and no further polishing or end preparation is required.

The second method of assembly uses a collar with a front cap containing a small flexible filler (rubber O-ring) (fig. 2(b), 3). The plastic fibers are intermixed (fig. 4(a)) and fed from the back of the collar through the O-ring (fig. 4(b)). The front cap is then screwed tightly against the shoulder of the main body of the collar (fig. 4(c)). Flat surfaces machined into the front end cap and main body of the collar enable these parts to be tightened with specially designed wrenches. Tightening down the end cap compresses the O-ring against the plastic fibers, securing them firmly. The plastic fibers are then cut flush with the front surface of the collar (fig. 4(d)).

Both the threaded collars and the collars with the O-rings can be reused many times to make new seals. Their external dimensions are comparable to those used with the epoxied glass fiber optic seals (fig. 1(a)). This comparability allows all the seals to be used with the same inspection and identification equipment. The threaded collar assembly is less expensive to produce than the collar with the

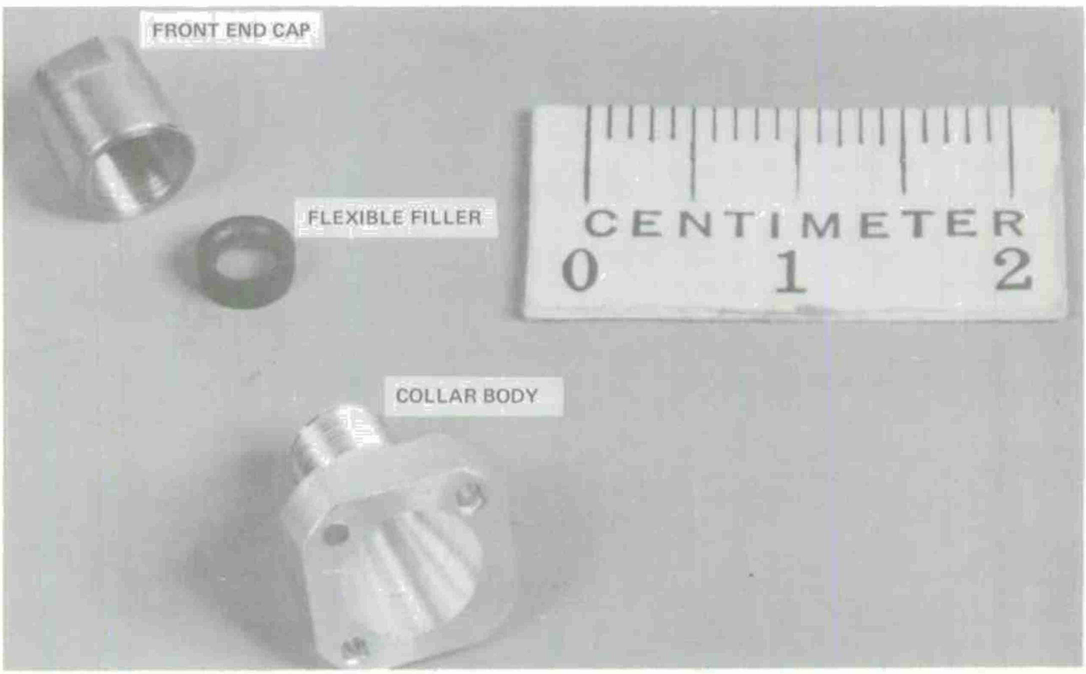

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Figure 3. Fiber optic seal collar components.

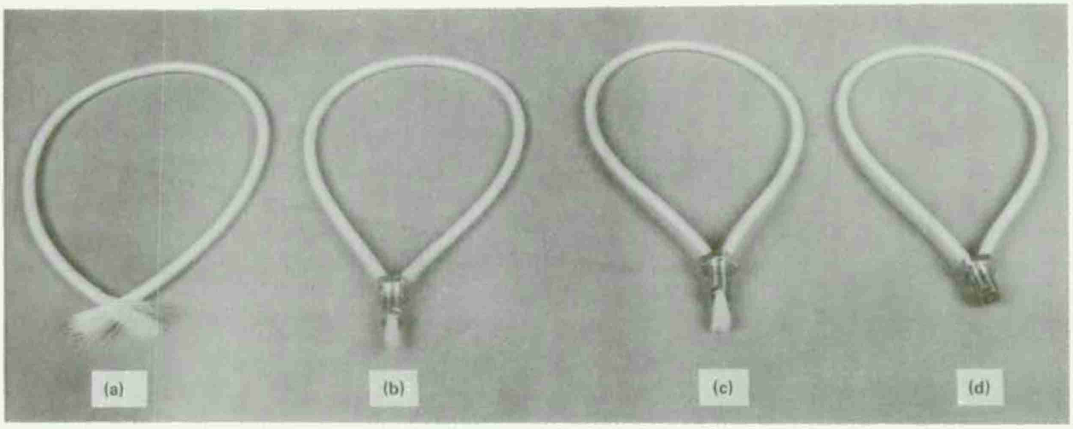

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Figure 4. Plastic fiber optic seal assembly procedure: (a) intermix fibers, (b) insert fibers into collar, (c) tighten front end cap, and (d) terminate fibers flush with front face.

O-ring assembly. However, the collar with the O-ring holds the fibers more securely, and the tightness of the fibers varies less from assembly to assembly. Since the end cap can be screwed down only until it hits the shoulder on the main body of the collar, the O-ring is compressed by the same amount in each seal. This increased insurance in dependability of the seal makes the O-ring collar assembly the preferable one for operational use.

An assembled plastic fiber optic seal with a collar containing a compressed O-ring is shown in figure 5. This seal consists of a plastic fiber optic bundle with 180 individual fibers of 0.005-in. diam. Seals with 0.010-in.-diam fibers did not provide sufficient fiber ends for reliable identification, whereas an excessive number of the 0.003-in.-diam fibers was required to fill the collar opening. When the plastic fibers with the threaded collars are used, both the larger, less-flexible, 0.010- and the smaller, 0.003-in.-diam fibers, which resist torsional stresses less, tend to break more easily as they engage with the threads than do the 0.005-in.-diam fibers.

The number of fibers required to fill a given size opening is proportional to the inverse square of the individual fiber diameter. The collars with the compressed O-rings were designed to hold 180 of the

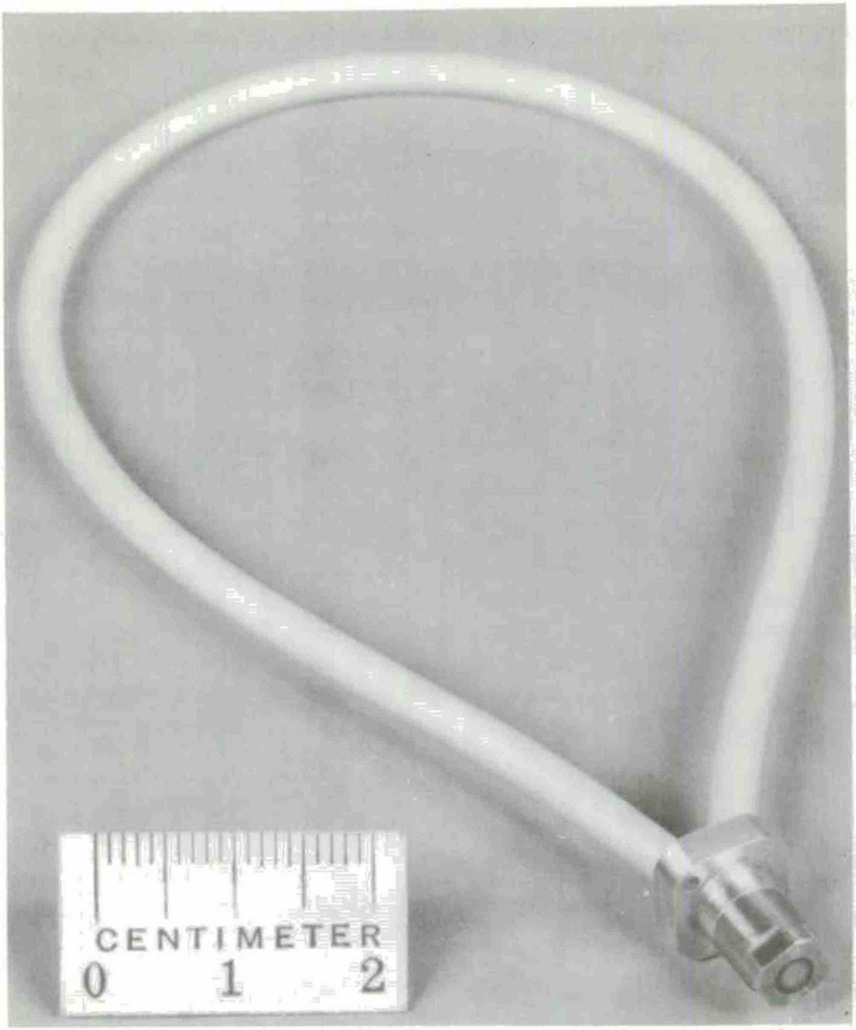

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Figure 5. Plastic fiber optic seal.

0.005-in.-diam plastic fibers, whereas the threaded collars hold from 150 to 180 of the 0.005-in.-diam fibers, depending on the hole and thread size at the front of the collar. Also, seals were constructed with fibers of several different diameters in the same bundle. A fiber bundle of 150 fibers of 0.005-in. diam was substituted by a bundle of 120 fibers of 0.005-in. diam and 80 fibers of 0.003-in. diam. The advantage of using different fiber diameters in the same bundle is that fibers of larger diameter (0.005 in.) produce a seal that is simple to assemble, whereas fibers of smaller diameter (0.003 and 0.001 in.) make it even more unlikely that the fiber bundle can be severed and rejoined in the field without noticeable signs of tampering.

Figure 6(a) shows the fingerprints of a plastic fiber optic seal in its two orientations under the identification system.* How much the fibers in this seal collar intermixed was revealed by cutting the fiber bundle and shining light into the two bundle sections. The resulting patterns formed at the viewing surface of the seal are shown in figure 6(b,c). The lit fiber ends in figure 6(b) originate from one

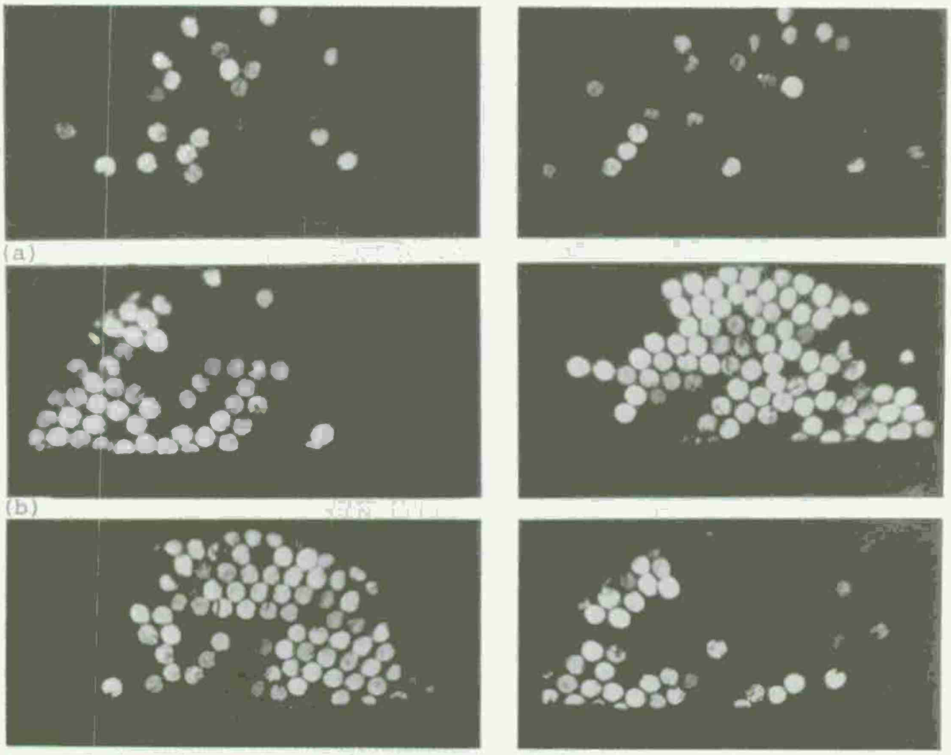

Figure 6. Plastic fiber optic seal. Row (a): Seal fingerprints (seal consists of 180 plastic fibers of 0.005 in.-diam). Rows (b) and (c): Indication of degree of fiber mixing; illuminated fibers with seal's fiber bundle cut in two and light shining into one of two resulting bundle sections in (b) and into other bundle section in (c). Left column: seal in one of its two possible orientations under identification system; right column: seal in other orientation.

**In the seal identification system, light is directed onto the fiber ends in half of the collar opening, while the fiber ends in the opposite half form a unique fingerprint. The seals are oriented by locator pins inserted into two small holes in the collar shoulder (fig. 2). Since the holes are located 180 deg about the collar axis, two precise orientations of the seals are possible. The illuminated half and the viewing half of the seal are reversed in these two orientations. An orientation indicator dot on the rear surface of the collar is used to distinguish one orientation from the other.*

end of the bundle that was looped into the collar to form the seal, and the lit fiber ends in figure 6(c) are from the other end. Together they represent all the fiber ends in the field of view of the identification equipment, except for those fiber ends associated with any broken or discontinuous fibers in the bundle. If there were no intermixing, the light centers in figure 6(b) would be in a separate adjacent region from those in figure 6(c). However, the actual patterns in figure 6(b,c) are not confined in adjacent regions, but are dispersed into each other, indicating considerable fiber intermixing.

The plastic fiber optic seals developed at HDL for ACDA are considerably easier to assemble in the field than the glass fiber optic seals. (Fibers are mechanically secured into the collar, and the ends are cut off with a sharp knife. No polishing is required.) The plastic fibers (1) intermix more easily and thoroughly than glass fibers in the seal assembly, (2) do not penetrate the skin during seal assembly, and (3) are difficult to break when the fiber optic bundle is bent or twisted. Very few fibers break while the seals are being assembled. The collars and a major portion of the plastic fiber optic bundles can be reused for new seals.

3.3 Assembly Procedure

The plastic fiber optic seals with the flexible filler (O-ring, fig. 2(b)) are assembled by the following steps:

(a) Cut the plastic fiber optic bundle to the desired length. Expose about 2 cm of fiber at each end of the bundle.

(b) Place the fiber bundle in its field location, and intermix the fiber ends (fig. 4(a)).

(c) Screw the front end cap onto the collar until the O-ring begins to compress. Twist the intermixed fibers slightly, and insert them into the rear of the collar. Push the fibers through the collar until the sheathing from both ends of the fiber bundle rests against the surface of the conical hole within the collar. The plastic fibers protrude through the front of the collar as shown in figure 4(b).

(d) Tighten down the front end cap with wrenches until it rests firmly against the shoulder on the main body of the collar (fig. 4(c)).

(e) Cut the fibers with a sharp knife flush with the front face of the collar (fig. 4(d)).

No polishing or further end finishing of the fibers is required. The assembly procedure applies also for plastic fiber optic seals with the threaded collars (fig. 2(a)) when steps (c) and (d) are changed as follows:

(c) Place cellophane tape around the intermixed fibers. Allow about 0.5 cm of the fiber length to extend beyond the tape.

(d) Insert the fibers into the rear of the collar, and screw the collar clockwise, engaging the fibers with the threads at the front of the collar.

4. FIBER OPTIC SEAL IDENTIFICATION SYSTEMS

4.1 Existing Systems

Three systems exist for inspecting, photographing, identifying, and verifying the HDL-developed field-assembled fiber optic seals (fig. 7). Figure 7(a) shows a seal inspection system incorporating a 30X enlarger camera that HDL delivered to ACDA in 1971. Figure 7(b) shows a small 30X hand-held viewer for direct viewing of the seal fingerprints. Figure 7(c) shows a compact seal identification system designed by Mitchell Photogrammetry, Inc., under subcontract to HDL.

The original system incorporating the 30X enlarger camera yields positive and negative Polaroid prints of the seal fingerprints. The negatives can be used as an overlay of subsequent positive prints to indicate simply and reliably the integrity of the seal. The size of the enlarger camera makes field use of the system somewhat cumbersome.

The compact seal identification system shown in figure 7(c) alleviates the size problem. The system consists of a small camera with a microscope objective that produces a negative of the seal's fingerprint magnified 10 times. Subsequent negatives of the same seal are viewed and compared with the original negative in a 3X viewer comparator. The viewer comparator projects a blue image of the original fingerprint negative and a yellow image of the subsequent fingerprint negative. If the two fingerprints are identical, the superimposed images appear as one black image. The system allows easy photographing of the seals, and the verification of the integrity of the seal fingerprints is reliable.

The portable film developing device, PoroPak processor model 35 IP (manufactured by PoroKem, Inc.), used to process the TRI-X No. 126 roll film, is very easy to operate and produces good quality negatives when the film is washed after processing. It is an excellent device for processing this type of film in the field. For

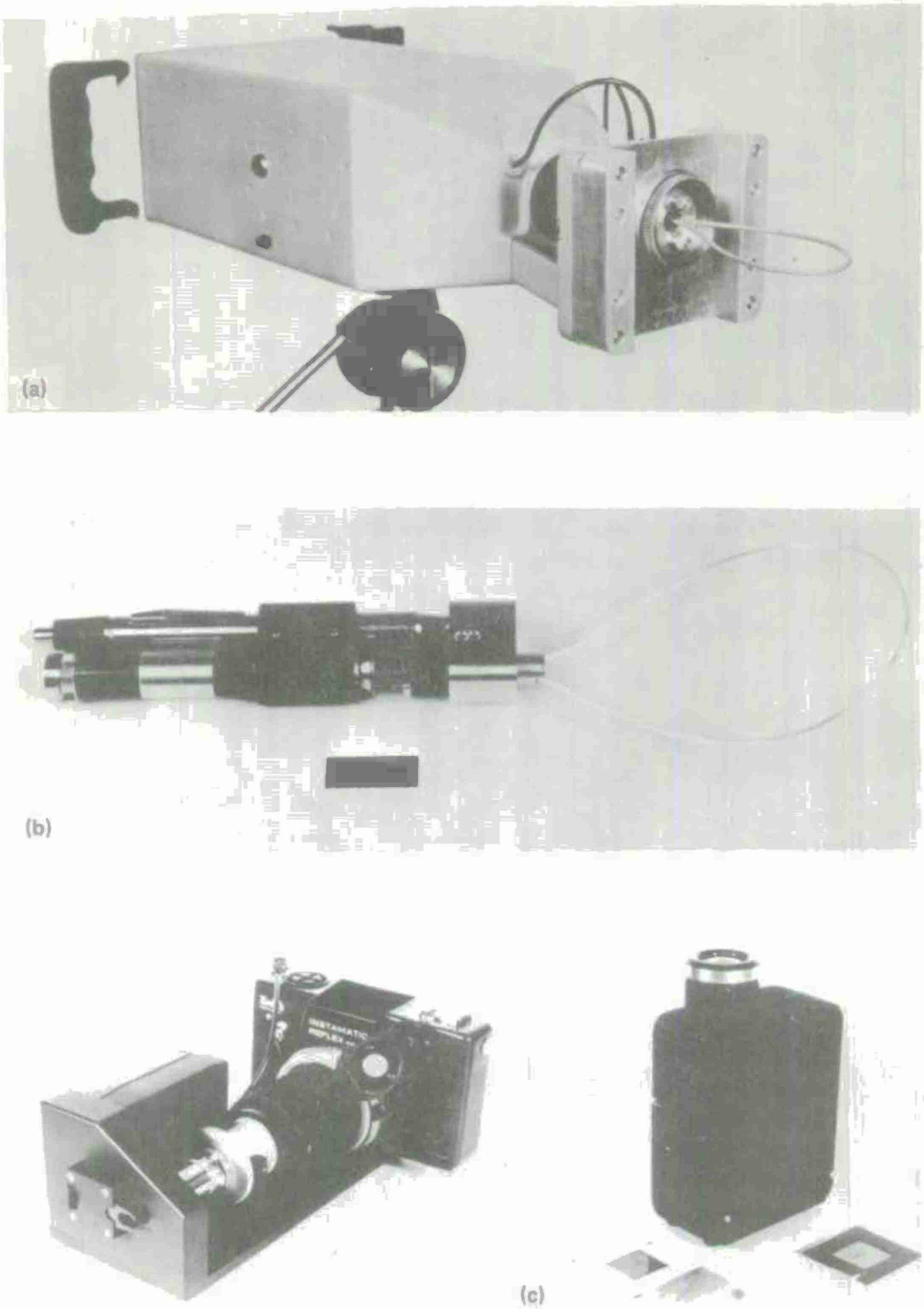

Figure 7. Fiber optic seal identification systems: (a) with 30X enlarger camera, (b) hand-held viewer, and (c) with 10X enlarger camera and 3X viewer comparator.

this seal identification system, the problem is not in the processing device, but in the need for film processing. The film requires 12 min for processing and additional time for washing and drying. The film then requires mounting to form slides that can be inserted into the viewer comparator. This procedure requires time and effort at the field location; they may be prohibitive when many seals have to be inspected and immediately verified for integrity.

In the HDL evaluation of existing systems for inspecting, photographing, and verifying the fingerprints of fiber optic seals, possible improvements and also entirely different concepts for seal identification systems were considered.

4.2 Proposed Seal Identification System for Operational Use

A laboratory setup of a compact and versatile seal identification system is shown in figure 8. The system is made up of the hand-held viewer shown in figure 7(b) and a lightweight camera with a Polaroid back that holds 3-1/4 × 4-1/4-in. film. The camera is designed for photographing the view seen through a microscope having a

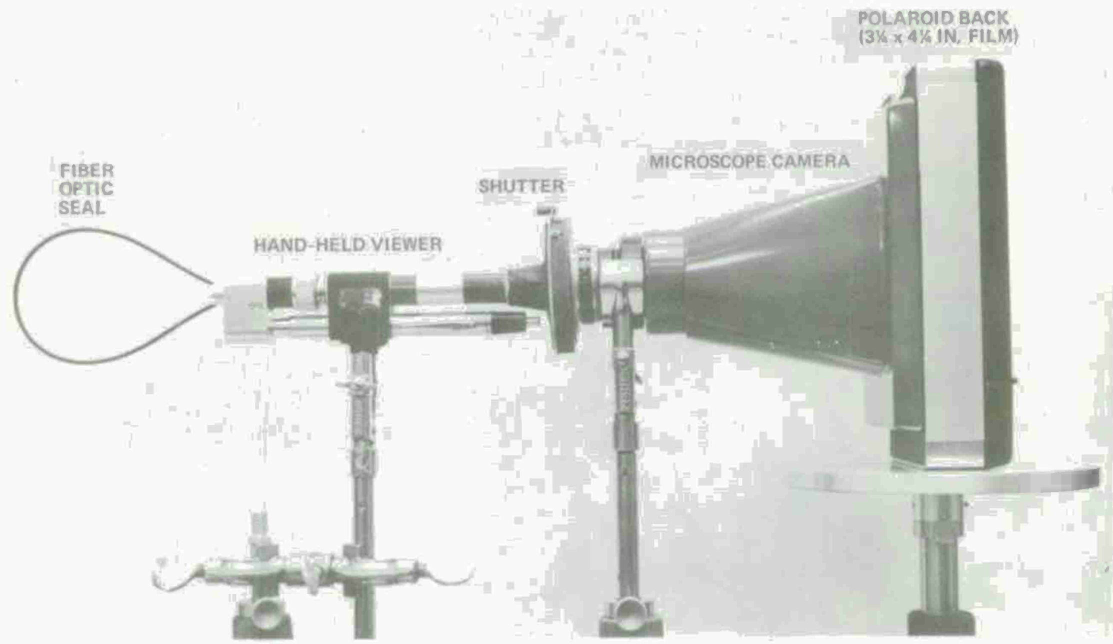

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Figure 8. Laboratory setup of compact seal identification system for viewing and photographing fiber optic seals.

standard diameter eyepiece. The standard eyepiece adapter was removed and replaced by a shutter and an improvised light-tight adapter for the hand-held viewer. This arrangement has the following advantages:

(a) The arrangement provides versatility through its three basic elements: the seal, the hand-held viewer, and the camera. When a photograph of the seal is required for further identification and integrity verification, the camera is held against the eyepiece, and the shutter is released.

(b) The system is compact, lightweight, and easy to use in the field.

(c) The photographs of the seals depict the same view as seen through the hand-held viewer. The viewing equipment and photographic equipment cannot possibly illuminate different parts of the seal.

(d) The camera uses small Polaroid film packets, 3-1/4 × 4-1/4 in. Both positive and negative prints can be obtained by use of type 105 P/N film (ASA 75). Also, standard type 107 film (ASA 3000) can be used for enhancing fibers with low light levels. Rapid verification of the seal's integrity is insured.

Under task ACDA-RA-178, HDL developed and fabricated two compact fiber optic seal identification systems based on the laboratory setup shown in figure 8. A completed model of the fiber optic seal inspection equipment is shown in figure 9. In this model, the hand-held viewer twists and locks firmly onto the camera assembly, and the seal is held onto the hand-held viewer by a spring clip holder. This arrangement allows the equipment to be held easily while the seals are viewed and photographed.

The compact system for fiber optic seal inspection has been packaged in a small suitcase along with a fiber optic seal assembly kit as shown in figure 10. The assembly kit is for seals consisting of plastic fiber optic bundles secured in collars with compressed rubber fillers as described in section 3.2. The assembly and inspection kit is intended for test and evaluation in the field. Certain field conditions, such as high radiation, will undoubtedly require further design modifications in the collars and in the assembly and inspection equipment.

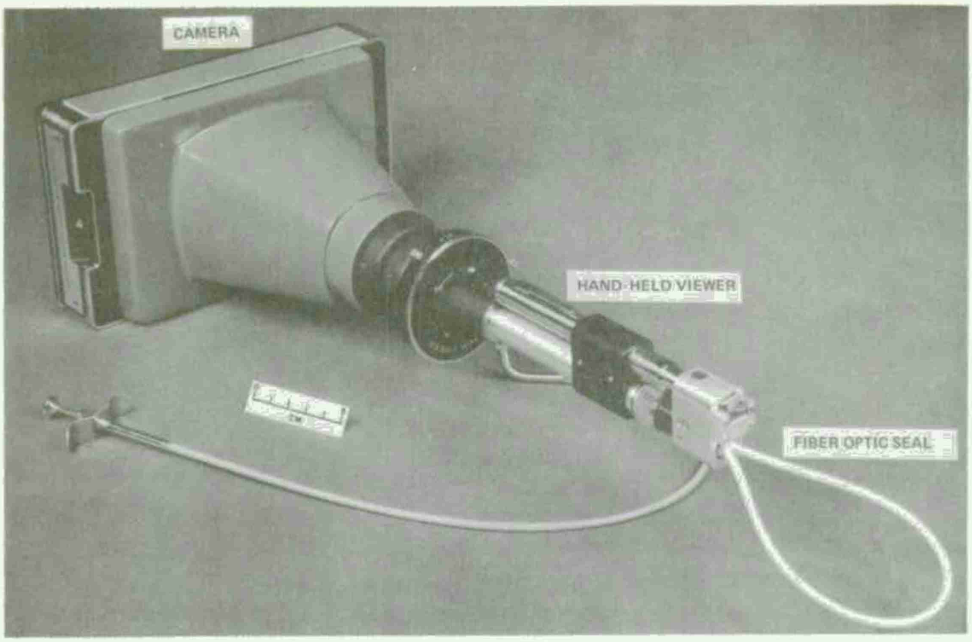

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Figure 9. Fiber optic seal inspection equipment.

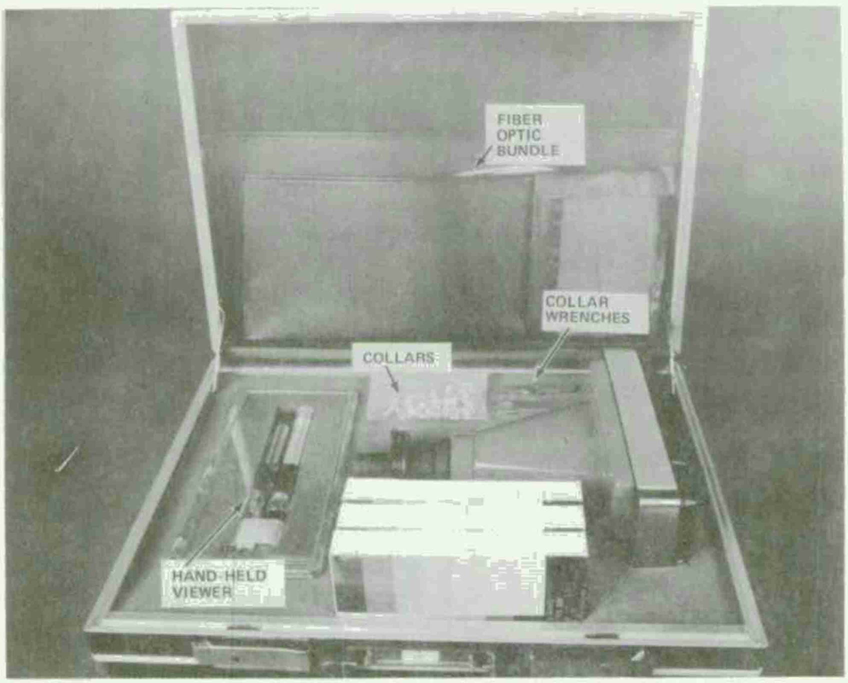

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Figure 10. Fiber optic seal assembly and inspection kit.

4.3 Seal Identification by Reticle Pattern Projection

In certain safeguards sealing situations, it may not be practical or feasible to photograph the seals. For such cases, Lorin R. Stieff has suggested an alternate method of seal identification in which a radial grid line is projected onto the seal fingerprint. One can rotate this grid line to a particular angular setting θ and note the radial distances r at which lit fiber ends occur. That way, characteristics of the seal fingerprint can be specified. In this scheme, one can identify the fiber optic seals and verify their integrity by checking the location of specific lit fiber ends and also noting any distinct striations or marks in these fiber ends.

For reticle pattern projections, small disks were cut from existing standard microscope reticles and mounted in the focal plane of the eyepiece of an existing hand-held viewer used with the seals. The reticle patterns were in sharp focus, but appeared dim over portions of the fiber otpic seal fingerprints, due to the low background light level. Side lighting of an etched glass reticle improved the visibility of the reticle somewhat for certain fiber optic seal fingerprints. Further investigations with reticles having suitably designed grid lines and patterns are required before the effectiveness of this method can be properly evaluated.

5. SUMMARY

Considerable progress has been made in developing a reliable tamper-resistant/tamper-indicating fiber optic seal that is simple to assemble in the field. Dependable seals that are easy to assemble have been produced from both glass and plastic fiber optics. Along with the seals, inspection equipment has been developed that is compact, is easy to use, and allows a reliable integrity check of the seal fingerprints. The fiber optic seals and related inspection equipment have reached a level of simplicity and reliability that makes them appealing for operational field use. Certain field conditions, such as high radiation, are expected to impose further design changes in the seals and the associated assembly and inspection equipment.

* * * * *

ACKNOWLEDGEMENT

The author is indebted to Frank Houck and Lorin Stieff of the ACDA for their continuing valuable direction and helpful suggestions. The author thanks also Charles Pruitt and Charles Rafferty of HDL for their help in constructing the seal collars and inspection equipment. Mr. Pruitt greatly simplified the assembly procedure of the plastic fiber optic seals by originating and designing the collar with the flexible rubber filler.

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